Renewable and Sustainable Energy Reviews 15 (2011) 956–963

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

On the use of wind energy to power reverse osmosis desalination plant: A case study from Ténès (Algeria)

Djamila Abdeslame Dehmas[a], Nabila Kherba[b], Fouad Boukli Hacene[b], Nachida Kasbadji Merzouk[a], Mustapha Merzouk[c], Hacene Mahmoudi[a,b,*], Mattheus F.A. Goosen[d]

[a] Wind Energy Division, Renewable Energy Development Center, BP. 62, Bouzaréah, Algiers, Algeria
[b] University Hassiba Ben Bouali of Chlef, Algeria
[c] Mechanical Department, University Saad Dahlab of Blida, Algeria
[d] Alfaisal University, P.O. Box 50927, Riyadh 11533,Saudi Arabia

ARTICLE INFO

Article history:
Received 20 September 2010
Accepted 4 November 2010

Keywords:
Wind energy
Desalination
Reverse osmosis
Wasp
RETScreen

ABSTRACT

The aim of this study was to provide a detailed analysis of wind energy resources for seawater reverse osmosis desalination (SWRO), in a case study region of Ténès Algeria, by using commercial Wasp software. An economic analysis of the environmental benefits was also done using RETScreen software to give details about financial investment hazards and CO_2 emissions reduction. An energy yield and economical analysis was performed of a hypothetical wind farm consisting of 5 wind turbines of type Bonus 2 MW. It was found that wind energy can successfully power a SWRO desalination plant in the case study region.

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1. Introduction

The economic and industrial potentials of renewable energies, such as geothermal, solar and wind, as well as the environmental advantages have been pointed out in several recent studies [1–5]. The first use of geothermal energy, for example, for electric power production occurred in Italy a century ago with the commissioning of a commercial power plant (250 kWe). Small decentralised water treatment plants can also be connected to a wind energy conver-

* Corresponding author at: Wind Energy Division, Renewable Energy Development Center, BP. 62, Bouzaréah, Algiers, Algeria.
E-mail address: usto98@yahoo.fr (H. Mahmoudi).

1364-0321/$ – see front matter
doi:10.1016/j.rser.2010.11.004

tor system. The wind turbines as well as the desalination system can be connected to a grid system [6]. The Kwinana Desalination Plant, for example, located south of Perth in Western Australia, produces nearly 140 ML of drinking water per day, supplying the Perth metropolitan area [7]. Electricity for the plant is generated by the 80 MW Emu Downs Wind Farm located in the state's Midwest region. Alternative energy sources such as nuclear also need to be considered [8]. The Shevchenko BN350 nuclear fast reactor and desalination plant, for instance, situated on the shore of the Caspian Sea, in Kazakhstan, during its lifetime of some 27 years could generate 135 MWe of electric power and provide steam for an associated desalination plant which produced 80,000 m^3/day of potable water [9].

With the world's fresh water demands increasing, much research has been directed at addressing the challenges in using renewable (and environmentally friendly) energy to meet the power needs for desalination plants. Lack of water, for instance, has caused great distress among the population in large parts of the MENA countries (Middle East and North Africa). Renewable energy technologies such as wind, solar, and geothermal and even alternatives such as nuclear show great promise for water [1,8–11]. They fall into two categories; the first includes distillation processes driven by heat produced directly by the renewable energy system (RES), while the second includes membrane and distillation processes driven by electricity or mechanical energy produced by the RES.

The coupling of renewable energies such as wind, solar and geothermal with desalination systems holds great promise for water scarce regions [2,12–14]. Solar energy can also be converted to thermal or electrical (i.e., photovoltaic) energy and then used in water desalination directly or indirectly, respectively [2,12,13]. It can be argued that an effective integration of these technologies will allow countries to address water shortage problems with a domestic energy source that does not produce air pollution or contribute to the global problem of climate change. Furthermore this approach will help to bypass the problems of rising fuel prices and decreasing fossil fuel supplies. Bourouni et al. [15–17] reported on installations using humidification dehumidification processes in the form of evaporators and condensers made of polypropylene and operated at a temperature between 60 and 90 °C. Recently, many medium and large scale water treatment and desalination plants have been partially powered with renewable energy mainly wind turbines, PV cells or both. The energy demand of, for example, the Sureste seawater reverse osmosis (SWRO) plant located in Gran Canaria, Canary Islands, of a capacity of 25,000 m^3/d is provided by a combination of PV cells (rooftop) and the rest from the grid which consist of an energy mix including wind energy [18,19].

2. Water crisis and desalination in the case study country

Algeria has an area of 2,381,741 km^2 and a population of about 33 millions. It is the Africa's second-largest country and the eleventh in the word in term of land area. The country is divided into four main physical regions. The first region located in the north is the Mediterranean coastline of 1200 km in length, where most of the country's population (80%) and industry are concentrated. The second region is the Tell which extends 80–190 km inland from the coast. The next region, lying to the south and southwest is the High Plateau; a highland region of level ground together with the mountains and massifs of the Saharan Atlas of the south region. The fourth region, comprising more than 80% of the country's total area, is the great expanse of the Algerian Sahara [20].

Desalination has become an imperative and inevitable solution for Algeria to overcome its current shortage of potable water. Having exploited seawater desalination largely for industrial use since the sixties, Algeria is now in a hurry to exploit this technology to quench the thirst of its citizens. The total production capacity of the operating plants in Algeria is 661,920 m^3/day. About 47% of it is produced by multistage flash (MSF) and multiple-effect distillation (MED), 44% by reverse osmosis (RO), 5.5% by vapor compression (VC) and 3% by electro-dialysis (ED). More than 67% of the total desalinated water is produced from seawater, 22% from brackish water, 8% from river water and the rest from other sources. The major user of the desalinated water is municipalities with about 49% followed by industries with 45%. The rest is by power, tourist places, military and other sectors.

The Ministry of Water Resources, through Algerienne des Eaux (ADE) and Algerian Energy Company (AEC), started recently the construction of many large-scale seawater reverse osmosis desalination plants. Among these, Hamma (Algiers), Beni-Saf, Mostaganem, Sidna Ouchaa and Honaine in Tlemcen, Cap Blanc and Ténès will supply 200,000 m^3/day each and Skikda, Douaouda, Cap Djenet will supply 100,000 m^3/day each. In order to carry out the large-scale desalination plants installed and under construction, the government approved the proposals according to BOO formula (Built, Own, and Operate) except the MSF plant constructed in the industrial zone of Arzew is in BOT (Built, Own, and Transfer) formula. This procedure will avoid risk of operation and maintenance problems due to lack of skilled manpower for the life of the plants which are estimated to be 25 years [20].

Ténès reverse osmosis desalination plant is located at 3 km from the town centre, with a capacity of 5000 m^3/d, it provides fresh water for some 40 thousands inhabitants. It was receipted on 2006. The plant consumes in average 7.27 GWh/year.

3. Wind power and desalination

Wind is generated by atmospheric pressure differences, driven by solar power. Of the total 173,000 TW of solar power reaching the earth, about 1200 TW (0.7%) is used to drive the atmospheric pressure system [21]. This power generates a kinetic energy reservoir of 750 EJ with a turnover time of 7.4 days. This conversion process mainly takes place in the upper layers of the atmosphere, at around 12 km height (where the 'jet streams' occur). If it is assumed that about 1% of the kinetic power is available in the lowest strata of the atmosphere, the world wind potential is of the order of 10 TW, which is more than sufficient to supply the world's current electricity requirements.

Kalogirou [22] argued that the world's wind energy could supply an amount of electrical energy equal to the present world electricity demand.

Different approaches for wind desalination systems are possible. First, both the wind turbines as well as the desalination system are connected to a grid system. In this case, the optimal sizes of the wind turbine system and the desalination system as well as avoided fuel costs are of interest. The second option is based on a more or less direct coupling of the wind turbine(s) and the desalination system. In this case, the desalination system is affected by power variations and interruptions caused by the power source (wind). These power variations, however, have an adverse effect on the performance and component life of certain desalination equipment. Hence, back-up systems, such as batteries, diesel generators, or flywheels might be integrated into the system.

Small decentralised water treatment plants combined with an autonomous wind energy convertor system (WECs) show great potential for transforming sea water or brackish water into pure drinking water [23]. Also, remote areas with potential wind energy resources such as islands can employ wind energy systems to power seawater desalination for fresh water production. The advantage of such systems is a reduced water production cost com-

pared to the costs of transporting the water to the islands or to using conventional fuels as power source.

Reverse osmosis is the preferred technology due to the low specific energy consumption. The only electrical energy required is for pumping the water to a relatively high operating pressure. The use of special turbines may reclaim part of the energy. Operating pressures vary between 10 and 25 bar for brackish water and 50–80 bar for seawater [6]. The Kwinana Desalination Plant, located south of Perth in Western Australia, is one example where wind power and reverse osmosis desalination have been successfully combined. The plant produces nearly 140 ML of drinking water per day [7]. Electricity for the plant is generated by the 80 MW Emu Downs Wind Farm located in the state's Midwest region. The reverse osmosis plant was the first of its kind in Australia and covers several acres in an industrial park.

The aim of this study is to provide detailed analysis of wind energy resources in the case study region using commercial Wasp software. Economical study using free RETScreen software can give details about financial investment hazards and CO_2 emissions reduction.



Fig. 1. Map of Ténès.

4. Methodology

The purpose of this study concerns proposition of electricity production from wind farm to power 5000 m^3/d reverse osmosis desalination plant. The tool used is the software package Wasp-4. Economical feasibility and greenhouse gases were analyzed using RETScreen free software.

4.1. Wind data and site description

The renewable energy resources of Algeria were estimated by the Renewable Energy development centre (CDER) since the nineties [24–26]. The particular interest of Algeria to develop the use of wind energy to produce electricity pushed scientists to identify sites with high wind potential [27–30].

Ténès is situated in the coastal region of Algeria with 21.5 km of shoreline (Fig. 1) The latitude and longitude of the location of data collection are 36°31.47′ N and 1°19.16′ E, respectively. It is at an elevation of 401 m above sea level. With regard to general weather conditions, the average temperature is 20 °C while the average pressure is 98.3 kPa, these data were used in the modelling [24].

The wind data used in this paper were obtained from the Ténès climatological recording station located in the southern direction at 3.5 km far from the sea at a height of 17 m. The latitude and longitude of the location of data collection are 36.5° and 1.33°, respectively (Fig. 2). The wind speed and direction were taken at regular intervals of 30 min [24]. In order to assure its reliability, the current study is the result of 5 years of measurements at regular intervals of 30 min starting from 2000 and ending in 2005.

4.2. Wind speed and the Weibull distribution

A random variable u, here the wind speed, has a Weibull distribution if its probability density function is defined by Justus et al. [32]:

$$f(u)=f(u,k,A)=\frac{k}{A}\left(\frac{u}{A}\right)^{k-1}\exp\left[-\left(\frac{u}{A}\right)^{k}\right],\quad v>0,\quad k,c>0 \tag{1}$$



Fig. 2. Wind farm site position.

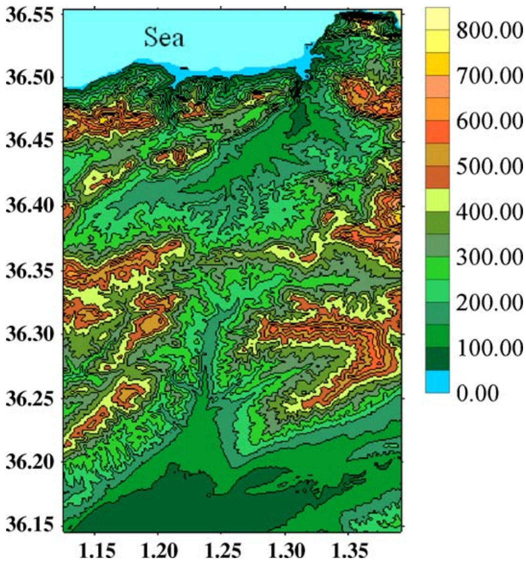


Fig. 3. Digital Elevation Model of the case study region.

where k is a so-called shape parameter (a dimensionless number) and A is scale parameter (m/s).

Using the Weibull distribution, the mean wind speed and the available wind power density in the site are given by the following relation:

$$\langle u\rangle = A\Gamma\left(1+\frac{1}{k}\right) \tag{2}$$

$$\langle P\rangle = 0.5\rho A^3\Gamma\left(1+\frac{3}{k}\right) \tag{3}$$

4.3. Wind rose, wind turbines configuration and energy yield estimation

The direction of the wind is of decisive significance for the evaluation of the possibilities of utilizing wind power. The direction statistics play an important role in the optimal positioning of a wind park in a given area. The Ténès wind rose and energy yield from a hypothetical wind farm of 10 MW installed capacity were obtained from the analysis of data using Wasp software [33].

4.4. Surface topography data

Digital Elevation Model (DEM) is a digital representation of ground surface topography or terrain. DEMs are used often in geographic information systems, and are the most common basis for digitally produced relief maps. Relief description is crucial to the spatial interpolation of wind speed at the study area (Fig. 3). Land topography has an important influence on the wind flow at atmospheric low layers; it can accelerate or decelerate the wind.

Relief information was given by the numerical treatment based on the maps provided by the Institut National de Cartographie at 1:2,000,000. Based on these results, one can say that the case study region is characterized by mountains which can reach 700 m of altitude.

Rougher surfaces are likely to cause more intense turbulence, which increases the wind speed across the surface. To assess the influence of roughness elements on wind speed measurements in the closer environment of the meteorological station, it is required to evaluate a roughness coefficient based on the standard aerodynamic roughness lengths [25] (Table 1), roughness was digitalized starting from the scanned topographic map and georeference under Wasp which is developed by the Danish Wind Energy Research Centre of Risø [31]. Roughness map is illustrated in Fig. 4.

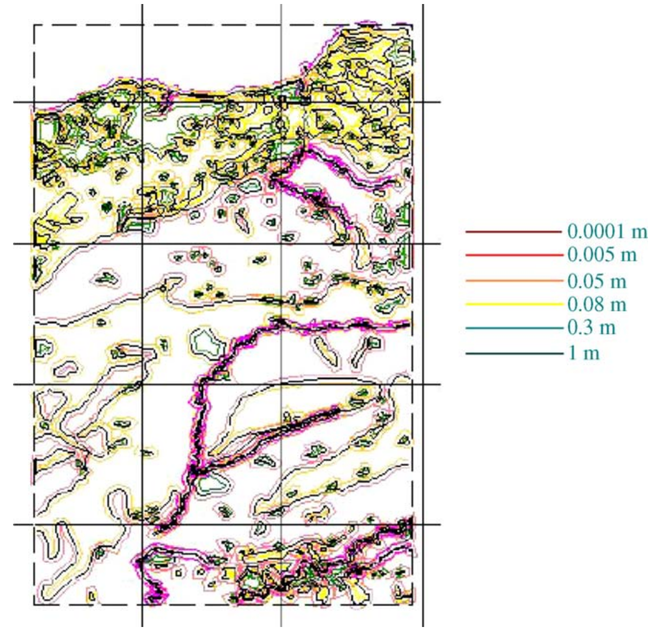


Fig. 4. Roughness lengths of the case study region.

4.5. Economical feasibility analysis and greenhouse gases

For economic simulation of the proposed wind farm, an MS Excel based clean energy project analysis software called RETScreen was employed [34]. The RETScreen International Clean Energy Project Analysis Software is an energy awareness, decision support and capacity building tool. The core of the tool consist of a standardised and integrated project analysis software which can be used world-wide to evaluate the energy production, life-cycle costs and greenhouse gas emissions reductions for various types of proposed energy efficient and renewable energy technologies compared to conventional energy projects [34].

5. Results and discussion

5.1. Wind speed and the Weibull distribution

The frequency distribution of the wind speeds help towards answering questions of how long is a wind power plant out of action in the case of lack of wind, and how often does the wind power plant achieve its rated output.

The analysis of Weibull parameters of the case study region shows that the shape parameter k and the scale parameter A are equal to 1.46 and 4.2 m/s, respectively. In Fig. 5, are shown histograms of the wind speed observations at the selected site over the collected period (2000–2005) together with fitted Weibull frequency function. By looking at Fig. 4, it is seen that the site of Ténès is characterized by high frequencies for smaller interval. Over 39% of the observations were between the 0 and 1 m/s range.

5.2. Wind rose, wind turbines configuration and energy yield estimation

The chart of the wind roses observed in Fig. 6 demonstrates that most of the wind flows from Southeast. It can be seen from Fig. 6 that 20.7% of the observed winds are in the sector 210 with a mean velocity of 5.02 m/s when 12.8% are in the sec-

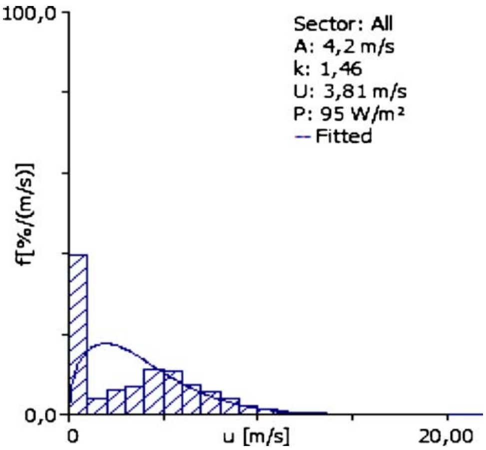


Fig. 5. Annual wind speed frequency with fitted Weibull distribution at a height of 10 m a.g.l.

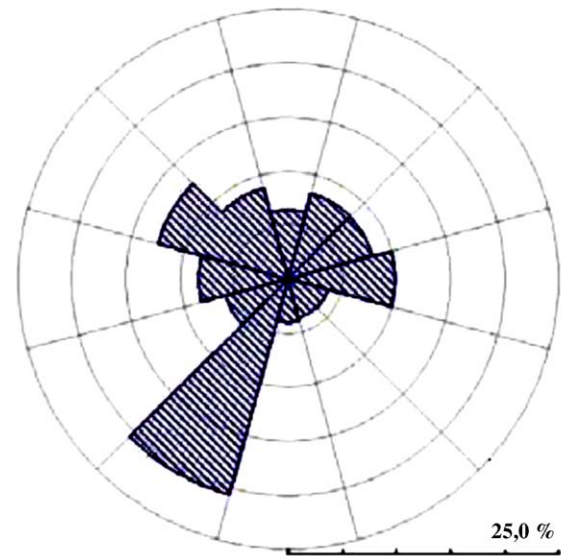


Fig. 6. Wind rose at a height of 10 m a.g.l.

tor 300° with a mean velocity equal to 5.09 m/s. In Fig. 7 are given the atlases of the wind speed, the energy output as well as the alignment topography of the five turbines in the case study region. The maximums wind speed and available energy output are reached in the south of the case study area are 6.54 m/s and 485 W/m^2, respectively. According to Fig. 7 one can say that the highest wind speed and available energy density are reached in the south of the case study area with respectively 6.54 m/s and 485 W/m^2.

The energy yield from a hypothetical wind farm of 10 MW installed capacity is obtained from Wasp [33]. In Table 2 are given, the geographic positions and altitude of each of the 5 turbines to be installed in the case study region as well as the corresponding shape parameter, the scale parameter and the mean wind speed with the corresponding available power density. Ruggedness Index (RIX) and wake loss give indication regarding the positioning of the turbines. Regarding data presented in Table 2 it is clear that turbine number 5 is the best positioned. In order to determine the energetic potentialities of the selected site, the atlas of the gross output and

Table 1
Considered aerodynamic roughness lengths Z_0 (m) [25].

Classes	Type of surface	Z_0 (m)
1	Cut grass, swamp areas	0.01
2	High growing, vines, bushes, few trees	0.10
3	Medium towns, towns, dense wood, forests	>1.25

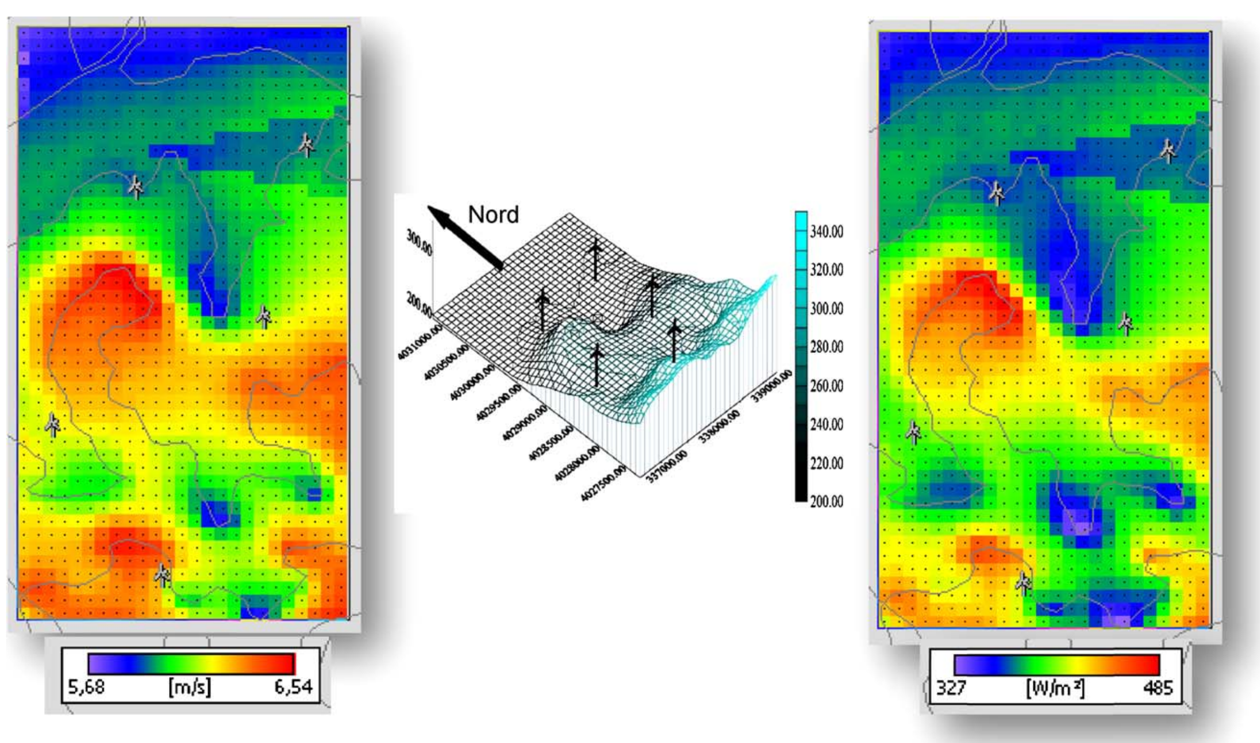


Fig. 7. Wind speed and available power density at the study site at 60 m a.g.l.

Table 2
Wec's main parameters estimation.

Turbine (N°)	Bonus 2 MW to height of 60 m a.g.l.								
	Location [m]	Elevation [m] a.s.l.	Net AEP [GWh]	*A* [m/s]	*k*	*U* [m/s]	*P* [W/m^2]	RIX [%]	Wake loss [%]
01	(337726.4, 4027327)	305	4.555	6.9	1.49	6.21	404	0.1	0.12
02	(338708.2, 4030251)	201	4.227	6.6	1.44	5.96	373	0.4	1.04
03	(337553.0, 4029968)	203	4.237	6.6	1.45	5.96	370	0.6	0.52
04	(338417.1, 4029086)	225	4.474	6.8	1.47	6.15	398	0.1	1.0
05	(336983.4, 4028348)	248	4.527	6.8	1.49	6.17	396	0.1	0.0

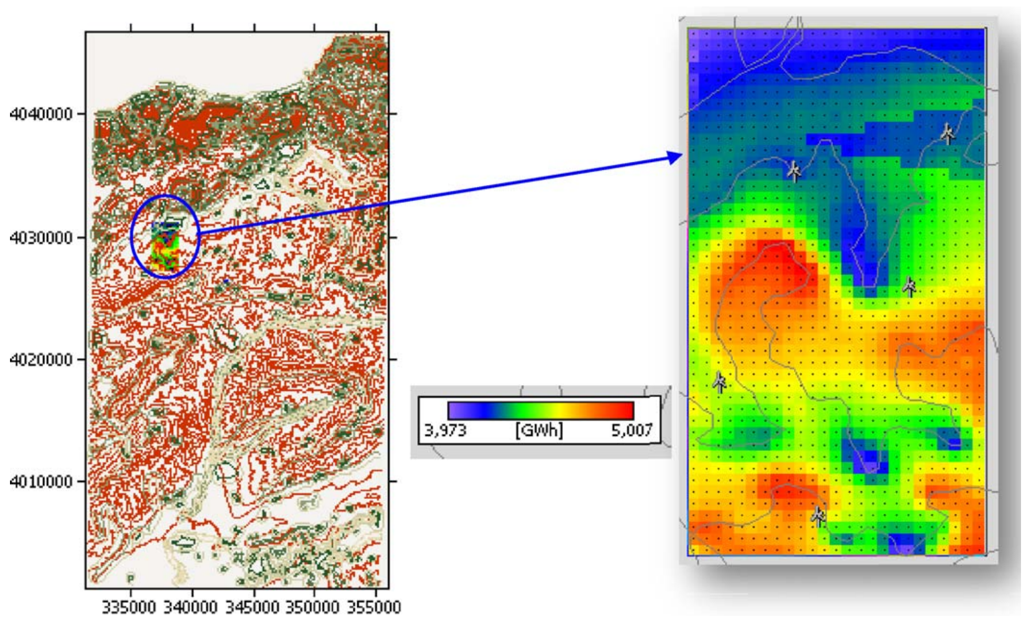


Fig. 8. Atlas of the electric output of the wind farm implanted at the selected site.

net electric of the wind farm estimated at, above the ground level (a.g.l.) is presented in Fig. 8.

It is noticed that the electric production reaches its maximum in the south of the area, where it approaches the 5 GWh. In addition, by considering the 5 turbines as installed on the site, the average energy production is about 17.5 GWh with wake's losses around 0.7%.

5.3. *Economical feasibility analysis and greenhouse gases*

The economical study was performed using RETScreen software and data resulted from Wasp's analysis. In another hand, various types of losses like array, airfoil soiling, down time and miscellaneous were also considered in the economical simulation and are summarized in Table 3. The gross output of electrical energy provided by the farm is estimated starting from the Wec's power curve (Fig. 9). The latter must be corrected by introduction of the correct atmospheric pressure and temperature of the implantation site, respectively 20 °C and 98.3 kPa. As seen from Table 4 around 59% of the total wind power plant cost accounts for energy equipment like wind turbines and other electrical equipment. The second major part of the cost of about 26.4% accounts for balance of plant

Table 3
Wind energy related coefficients used in energy yield estimation.

Item	Value
Array losses (%)	0.66 (calculated from Wasp)
Airfoil soiling (%)	2
Downtime losses (%)	2
Miscellaneous losses (%)	3

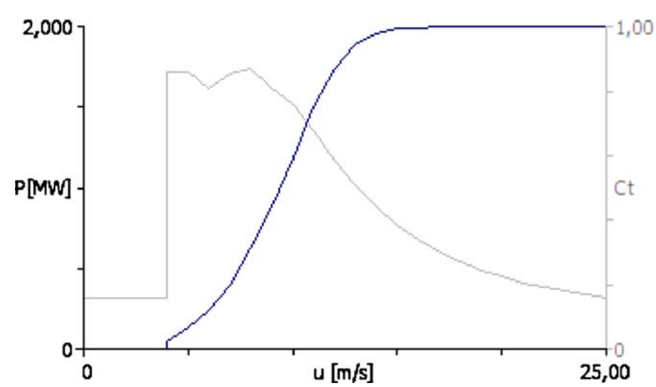


Fig. 9. Wind power curve of Bonus 2 MW wind turbine [33].

(BOP) cost. The inflation and discount rates of 2.5% and 12%, used in the present study, along with other cost parameters are summarized in Table 5. Simple payback represents the length of time

Table 4
Cost of wind farm development [34].

Item description	Cost (US $)	Of total cost (%)
Feasibility study	195,200	0.9%
Development cost	770,500	3.5%
Engineering cost	610,500	2.7%
RE equipment	13,143,000	59%
Balance of plant cost	5,868,000	26.4%
Miscellaneous	1,677,857	7.5%
Total initial cost	22,265,057	100%

Table 5
Summary of economic input parameters for cost analysis [34].

Items	Value
Avoided cost of energy ($/kWh)	0.1416
RE production credit ($/kWh)	0.025
RE production credit duration (year)	15
RE credit escalation rate (%)	2.5
GHG emission reduction credit ($/t$CO_2$)	5.0
GHG reduction credit duration (year)	21
GHG credit escalation rate (%)	0.0
Energy cost escalation rate (%)	5.0
Inflation (%)	2.5
Discount rate (%)	12
Project life (year)	25

Table 6
Wind energy production of the 10MW.

Item	Value
Gross annual energy production (MWh)	17,673
Annual energy production at local conditions (MWh)	16,800
Net annual energy production (MWh)	14,459
Simple payback (year)	13.3

Table 7
Green house gases reduction due usage of Wec's farm.

	1 year	21 years	25 years
Green house gases reduction (tons)	8588.46	180,358.00	214,711.53

that it takes for an investment project to recoup its own initial cost, from the cash receipts it generates. A shorter payback period means a desirable investment [35]. The simple payback for the proposed wind energy park calculated by the RETScreen model was found equal to 13.3 year (Table 6). Compared to the project life given in Table 5 the project seems economically feasible.

The greenhouse gases (GHG) pollute the environment (air, water and soil), which ultimately adversely affects the life of human beings. An indirect or hidden cost, which is not taken into consideration while using fossil fuels, is paid by the human beings [36]. The amounts of green house gases which could be avoided as a result of usage of 10 MW power plants at Ténès site are given in Table 7. From this analysis it was observed that a total of 8588.46 ton of green house gases could be avoided entering into local atmosphere each year if 5 Wec's each of 2 MW capacity are installed.

6. Concluding remarks

The use of wind potential as source of energy for the Ténès site situated in northern Algeria has been broadly assessed. Analysis results show that there are good prospects for wind energy utilization at the case study region. Wind power could provide a viable substitute to diesel oil for irrigation pumps and electricity generation.

Much research has been directed at addressing the challenges in using renewable energy to meet the power needs for desalination plants. Wind energy is a promising clean and renewable fuel source. The present study performed the energy yield and economical analysis of a hypothetical wind farm consisting of 5 wind turbines type Bonus 2 MW. The feasibility of using wind energy to power reverse osmosis desalination plant with daily capacity of 5000 m^3 implanted in coastal region of the case study country of Algeria was also analyzed.

In closing, analysis results show that there is great potential for the use of wind energy to power the RO desalination plant at the case study region with an electric kWh at 7c$. This confirms that wind energy remains the most promising source for electricity production with integration in the grid.

It can be concluded that, present region is suitable for the plantation of wind energy turbines to power reverse osmosis desalination plant.

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